An Expanded Model for SAR Countermeasures

December 1999

Contract # W7714-7-0114

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Executive Summary

The Electronic Countermeasures Section at the Defence Research Establishment Ottawa is actively conducting research into electronic countermeasures techniques, technology and architectures to meet the *synthetic aperture radar* (SAR) threat.

This report describes recent progress on the compensation of differences in SAR focusing parameters between the jammer and false target positions. This compensation is essential for accurate placement, formation and focusing of the deceptive false targets which may be projected large distances from the jammer site.

The importance and origins of differences in SAR focusing parameters at different locations can be best understood by introducing a basic model which is then expanded to a more sophisticated model. The first model, which we will call the *basic SAR ECM model* is sufficient for many simple cases and was the basis for early ECM experiments with simple geometries. The second model, which we will call the *expanded SAR ECM model* inherently incorporates compensation of SAR focusing parameter mismatch and is the basis for accurate placement, formation and focusing of deceptive SAR ECM false targets at arbitrary offsets and geometries.

The basic SAR ECM model uses a constant repeat delay to place a false target in range and produces an azimuth offset by applying a constant Doppler shift to the return pulse. ECM is transmitted only during mainbeam illumination of the jammer. This model can effectively generate targets close to the jammer position, but breaks down when attempting to create targets with large range and azimuth offsets. Targets which are displaced large distances in range are distorted and unfocused, and typically have undesired azimuth shift. The maximum azimuth offset distance in the basic model is approximately the azimuth mainbeam width, and even targets offset in azimuth within this limit have lower focussed power and may generate unwanted artifacts.

The expanded SAR ECM model corrects these problems by using suitable time-varying delay and Doppler profiles and allowing the jammer to transmit even when it is outside the SAR mainbeam.

Use of a Doppler compensation profile and repeat delay profile gives the jammer the flexibility to more correctly emulate a distant point target so that countermeasures appear properly focused and in the right position. The ECM Builder software tool calculates the delay, Doppler compensations and ECM transmit schedule by simulating the SAR imaging geometry. This removes the blurring, distortion and azimuth shift associated with large range offsets.

For a jammer to place a false target at a particular location it must transmit while the *target* location is illuminated by the SAR antenna. Targets with azimuth displacements greater than the azimuth mainbeam footprint will not be illuminated at the same time as the jammer, so the jammer must transmit outside the mainbeam illumination time (i.e. in side lobes). The ECM Builder program automatically calculates the required ECM transmission schedule.

The expanded SAR ECM model relies upon knowledge of platform trajectory. The more accurately the trajectory is known, the further deceptive false targets may be displaced. More research is required to better quantify the effects of platform trajectory errors for various basic geometries.

Implementing the techniques based upon the expanded SAR ECM model for targets with large range offsets is fairly simple, as most jammers are capable of implementing a linearly changing repeat delay and arbitrary Doppler profile. However, realizing the transmission period shift for large azimuth offsets is more difficult. Further work is needed to add the ECM transmission scheduling capability to jammers.

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1.0 Introduction

1.1 Background

The Electronic Countermeasures Section at the Defence Research Establishment Ottawa is actively conducting research into electronic countermeasures techniques, technology and architectures to meet the synthetic aperture radar (SAR) threat. This type of radar poses a significant threat from a tactical viewpoint and a significant challenge for the creation of countermeasures. The operation and features of synthetic aperture radar differ greatly from ordinary pulsed Doppler, CW and other non-imaging radar types. Many ECM techniques which are applicable to other radars are ineffective against SAR systems, and research has been conducted to create new and effective techniques.

Deceptive SAR countermeasures are intended to introduce realistic false targets into SAR images. For highest utility, it is important that a user of deceptive countermeasures be able to place false targets at known locations far from the jammer site. An important area of investigation is how to prevent de-focus, distortion and incorrect placement of these distant false targets.

1.2 Scope

This report describes the origin of focusing and placement problems for distant false targets as a mismatch in SAR processing parameters between the jammer location and the desired false target location. It outlines why these SAR parameters are not the same at different positions in an image and how these differences cause de-focus and placement problems. The report presents means of calculating and applying compensations so that ECM transmitted from the jammer site results in well-formed, focused deceptive false targets placed at the desired locations.

While the report mentions some implementation issues and suggests directions for implementation research, jammer implementation is outside the scope of this report. Though the discussion focuses on airborne and spaceborne strip-mapping SARs, many of the concepts introduced are valid for other types of SAR, such as spotlight, interferometric SAR or moving target indication. Some related topics, such as slide techniques, Computed ECM and SAR geometry and processing are excluded from the current discussion, but are discussed in [1, 2, 3].

1.3 Approach

The discussion introduces a basic model of SAR ECM which uses constant delay and Doppler offsets. The report then describes an expanded model which overcomes the limitations of the basic model by employing time-varying delay and Doppler profiles applied to returns transmitted during the *target location's* mainbeam illumination period (as opposed to the *jammer* illumination period).

The major features of the expanded SAR ECM model are the use of a time-varying range delay, the time-varying Doppler profile and the transmission scheduling. This report introduces each of these important features of the expanded model in turn, explains why the new features are necessary and describes how important parameters are determined. Finally, major conclusions are presented along with recommendations for future work.

2.0 The Basic SAR ECM Model

2.1 Overview

Early SAR ECM experiments were based on a fairly simple model of target placement. According to this model, applying a constant repetition delay will produce a constant range offset from the jammer location. Similarly, applying a fixed Doppler offset will move the target a fixed distance in azimuth.

Furthermore, the basic model assumes that the jammer can only transmit when it is strongly illuminated by the SAR antenna main-beam. In practice, this is done by setting the capture-and-repeat to occur only when the received signal strength exceeds a pre-determined threshold. Figure 2.1, below, summarizes the basic model.

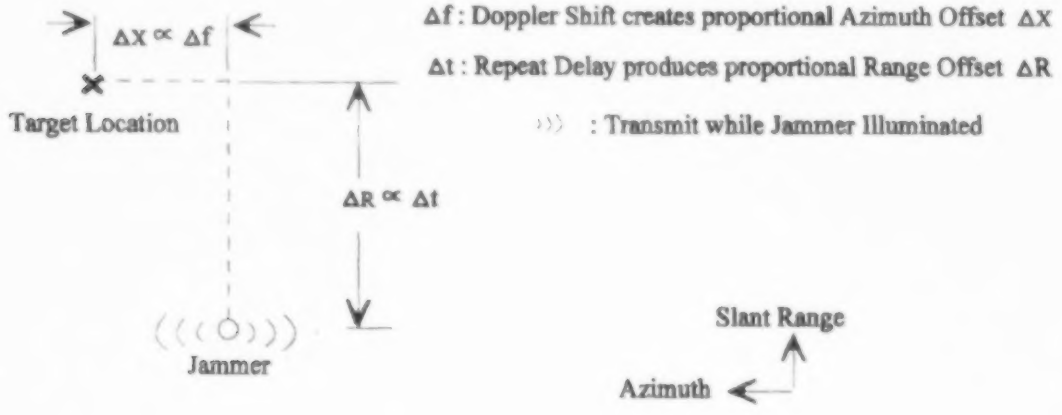


Figure 2.1: The basic model uses a fixed repeat delay to generate a range offset and a fixed Doppler shift to generate an azimuth offset.

The basic model works well when targets are displaced short distances in range and azimuth. For larger displacements, however, the basic model begins to have problems. Targets which are displaced a significant distance in azimuth become faded and sometimes appear at the wrong position. Targets displaced large distances in range are blurred, distorted and have undesired azimuth offsets. The basic model breaks down at large offsets because some of its implicit assumptions no longer hold under these conditions. Section 3.0 explains these limitations and outlines how the expanded model overcomes them.

2.2 Range Offsets in the Basic Model

Jammer repeat delays are commonly used to produce false targets at a range offset. The idea in SAR ECM is no different - the return signal should be delayed so that it reaches the SAR platform at the same time as the returns from the target location. The exact delay amount can be calculated using equation 2.1, below:

$$\Delta T = \frac{2}{c}(r_t - r_j) \qquad (2.1)$$

Where **c** is the speed of light, $\mathbf{r}_t$ is the range from the platform to the target location, and $\mathbf{r}_j$ is the range from the platform to the jammer [1]. In situations where the range to the target is less than the range to the jammer, a pseudo-negative delay can be created by sending the return pulse at the desired amount of time in advance of the next incoming pulse.

The basic model assumes that the value $(r_t - r_j)$ is constant over the observation time of the radar as the platform moves. As we shall see in section 3.2, this is not true and the assumption leads to focusing problems in many cases.

2.3 Azimuth Offsets in the Basic Model

In SAR, unlike other radars, applying a small Doppler shift to the return signal will move the focused target proportionally in azimuth. This occurs because a SAR relies on the phase characteristics of the return signal to place targets in azimuth. Any point target will return a natural frequency chirp pattern in the azimuth direction over the illumination period due to the platform motion and the side-looking geometry of the SAR. This azimuth chirp is *focused* by correlating it with the expected chirp pattern. A more detailed description of azimuth focusing is provided in [1]. Applying a Doppler to the returns creates a shift in the correlation spike, which translates to a shift in azimuth position. The size of this shift depends on the slope of the expected chirp, the amount of the applied Doppler, and the ground-speed of the SAR platform. The relationship is defined in equation 2.2:

$$\Delta f = \frac{\Delta x \cdot FMR_t}{V_p} \qquad (2.2)$$

Here, $\mathbf{\Delta x}$ is the desired azimuth offset, $\mathbf{V}_p$ is the ground velocity of the SAR platform, and $\mathbf{FMR}_t$ is the Doppler frequency modulation rate of the target location due to the motion of the platform.

[1] For a flat-earth case, the slant range values in Equation 2.1 can be calculated as the ground-range multiplied by the sine of the incidence angle.

The basic model relies on a number of assumptions to predict Doppler offset:

1. FMR_t is the same as the FMR at the jammer location, regardless of range displacement;
2. Doppler aliasing will not occur at the radar when Δf is applied;
3. The jammer and target location are illuminated by the radar over the same time period.

As we shall see in Section 3.3, equation 2.2 will produce useful results only within a restricted set of conditions.

3.0 The Expanded SAR ECM Model

3.1 Overview

In order to focus false targets at large range and azimuth offsets it is necessary to use a more sophisticated model of SAR countermeasures. The expanded SAR ECM model surpasses the placement limits of the basic model by avoiding its simplifying assumptions. In order to allow placement of focused targets at large range offsets, the model uses suitable time-varying delay and Doppler shifts. A time-varying delay profile is used to compensate for the time-varying range difference between the jammer and target location. A time-varying Doppler profile is applied to account for the varying Doppler frequency differences between the jammer and target locations over the target illumination time. The model also extends azimuth placement ability by shifting the jammer transmission period from the illumination period of the *jammer* location to the illumination period of the *target* location. Figure 4.1 summarizes the features of the expanded model:

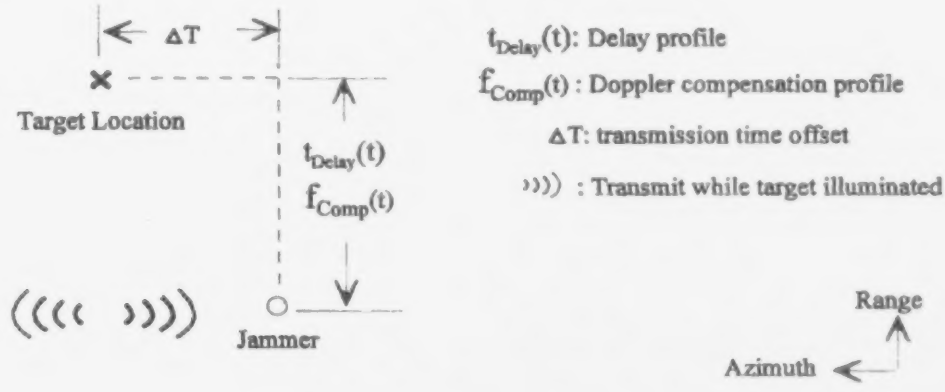


Figure 3.1: The expanded model uses time-varying delay and Doppler profiles transmitted over the target illumination period.

Moving from the basic model to the expanded model involves a change of viewpoint. The earlier model is jammer-centric, with a focus on generating offsets from the jammer position. While relatively easy to understand, the basic model lacks accuracy and target fidelity. The expanded model is target-centric, with the focus on manipulating the jammer transmissions so they properly emulate the returns from a possibly distant target. The new model is more complex and more difficult to calculate than the older model, but this is more than offset by the capability of a software tool, called ECM Builder, which is able to perform the calculations automatically. ECM Builder was produced by VPI under contract to DREO for the specific purpose of performing compensation calculations. The reward for the increased complexity of the expanded model is the ability to accurately specify how to place focused targets at large range and azimuth offsets.

The expanded model uses predictions of the SAR platform trajectory to calculate compensation parameters. Errors in the predicted trajectory will therefore introduce errors in the compensation parameters. These errors will be more significant for target locations further from the jammer. Therefore, if the trajectory prediction is of low quality, the area around the jammer within which focused deceptive countermeasures can be reliably produced will be smaller. If the trajectory information is extremely poor, the jammable area might be only slightly larger than achievable using the basic SAR ECM model. Not enough research has been conducted at this time to quantify the relationship between trajectory prediction quality and maximum displacement in range and azimuth. The relationship will be different for airborne and spaceborne cases, and will also depend on radar range.

3.2 Motivation for Time-Varying Range Delay

The expanded model replaces the constant repeat delay of the basic model with a suitable varying delay profile applied over the time the radar illuminates the target position (i.e. the delay is updated on each pulse). The basic model assumes that the difference in jammer and target slant range can be considered constant over the target observation time. Unfortunately, this is often not the case. Even though the *ground range* between the jammer and target location is constant, the range difference *as seen from the SAR platform* is not constant. To clarify this concept, consider the example of a car approaching two trees along a road. The first tree, an oak, is located 10m measured perpendicular from the road, while the pine is 20m from the road. When the car is far away, the pine is only slightly further from the driver than the oak As the car moves closer, however, the range difference increases to a maximum of 10m when the trees and car are colinear. Figure 3.2 below, is a graphical representation of the situation.

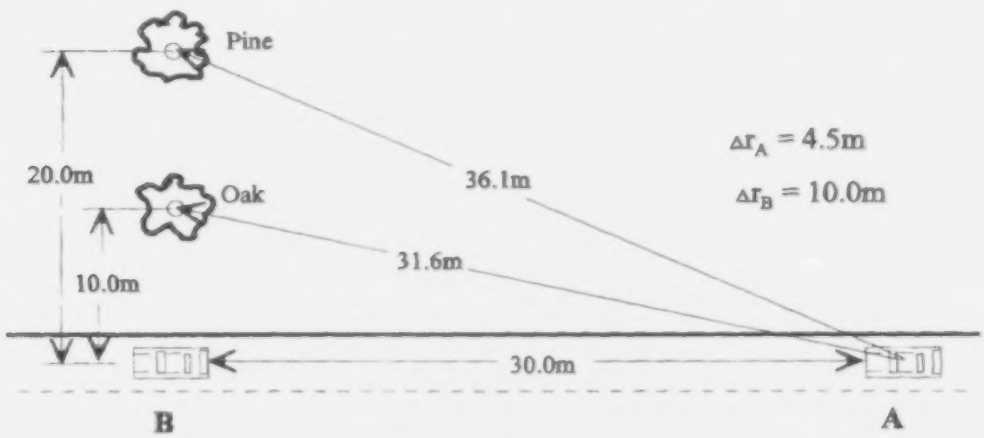


Figure 3.2: Range difference changes depending on platform position

In the car and trees scenario, the range to the closest tree decreases more rapidly as the car approaches a broadside view. The geometry of side-looking SAR systems produces the same effect: the range to a surface point close to the ground-track changes more quickly over time than the range to a more distant point. When the ranges to the two points are plotted over time, the range versus time curve of the nearer point is steeply curved, whereas a more distant point has a shallower range curve. Figure 3.3 illustrates this effect.

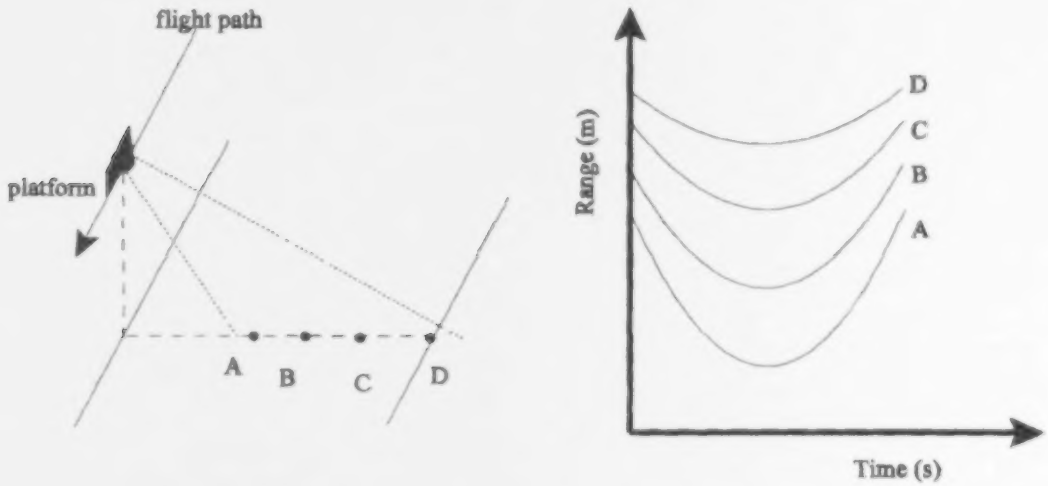


Figure 3.3: The relative range curves of distant and nearby surface points.

For a given SAR imaging scenario, a range curve is associated with every surface point. The SAR processor calculates the range curve associated with different surface points and compensates for the range variation. An important consequence of this is that the apparent range of a false target needs to follow the expected range curve for a surface point at the target location.

The range curve of the jammer location and the target location will normally have a different range offset and a different shape. A repeater-type ECM signal naturally inherits the range curve of its jammer location. Using a constant delay on the return signal can shift the perceived ECM range curve up or down, but will do nothing to correct the shape. At range offsets which are a small fraction of the overall range to the radar, the difference will not be significant; however, the mismatch gets larger as the repeat delay increases. Figure 3.4 shows the range curves for short and large offset cases.

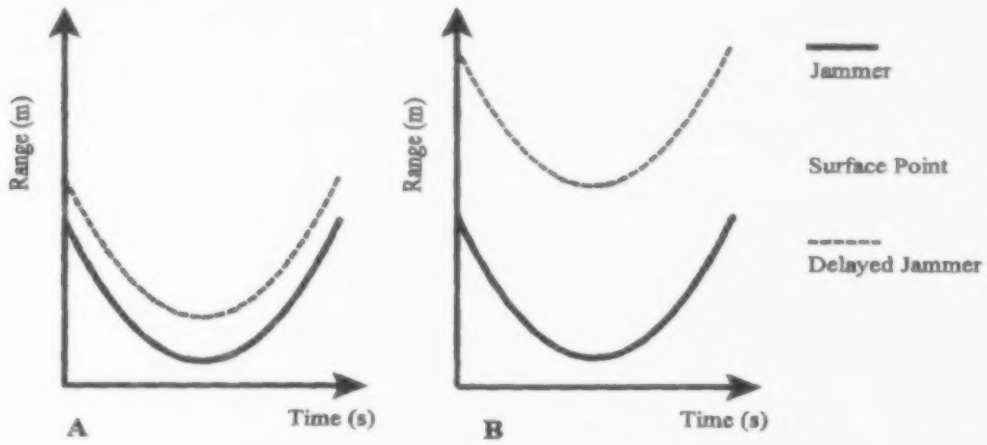


Figure 3.4: The delayed range curve fits adequately for a small offset (A), but not a large offset (B)

The mismatch between the ECM range curve and the expected range curve will cause problems if it produces a range difference larger than a range gate. In this case, some of the false target returns will occupy the wrong trajectory in the raw SAR data, resulting in blurring in both range and azimuth.

Whether this will occur depends on the imaging geometry, the SAR beam width and the range gate spacing. The larger the slant-range offset relative to the jammer range, the greater the difference in range curve shape between the jammer and target location. Also, SAR with a wider beam width will tend to integrate returns over a larger section of the range curve, revealing differences in shape. These difference are more likely to cause returns to fall into the wrong bin if the range bins are closely spaced. Because of these factors, the difference in range curve shape between the jammer and target location is more significant for airborne as opposed to spaceborne SAR platforms, and high resolution as opposed to moderate resolution radars.

3.3 Determination of Time-Varying Range Delay

The correct repeat delay at any point in time depends only on the difference between jammer and target range, which was shown to be a time-varying quantity in section 3.2. Therefore, finding a formula for the range difference over time is the central problem in determining the range delay profile. The range difference between the jammer and target location over time can be determined by finding the individual range profiles of the jammer and target locations and subtracting them.

There are a number of possible ways of calculating range behavior of a surface location over time:

1. closed form algebraic equations
2. measurements on the received radar return data
3. numerical modeling of the platform/target geometry in 3-D space over time

Method 1 is usually mathematically cumbersome and requires multiple simplifying assumptions to make the problem tractable. Unfortunately, these assumptions limit the generality of the resulting equation. This approach also depends upon knowing the SAR platform trajectory. Nonetheless, this method is used by many SAR processors.

Method 2 is often used to refine the predictions of the closed-form equations, but requires access to radar returns from the surface of the earth, which is not available for operational ECM.

Method 3 is very general and is made practical by the availability of off-the-shelf software tools such as the Hipparchus® library to model satellite orbits and solve 3D geometry [4]. Like method 1, this approach relies on the availability of a platform trajectory estimate.

Regardless of how the surface point to platform range values are obtained, it is again useful to consider the range over time geometrically, as a curve. The range curve for a typical surface point is shown in Figure 3.5, below.

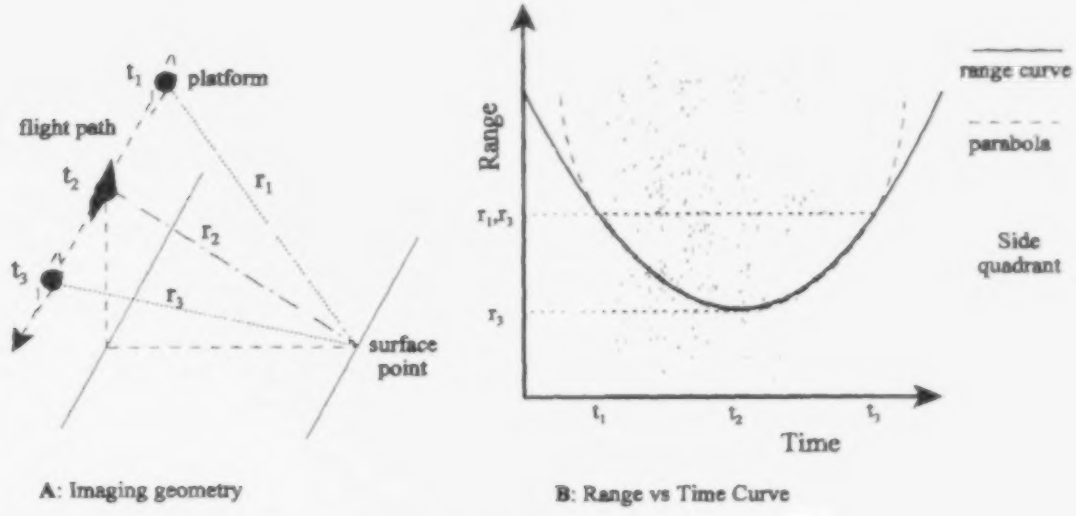


Figure 3.5: Side-looking part of range curve approximates a parabola.

Note that while the surface point is within the side-looking mainbeam, the shape of the range curve is very close to a parabola. This similarity suggests parameterizing the range curve as a quadratic polynomial equation.

The range curve of a surface point can be represented in polynomial form by Taylor-series expansion about the point of interest. In this case, the period of interest is when the target surface location is in the centre of the SAR mainbeam. The result of the Taylor-series expansion is an equation of the form

$$r(t) = a_0 + a_1(t - t_c) + a_2(t - t_c)^2 + \ldots \qquad (3.1)$$

Here, t_c is the beam-centre time of the target location and the a_x coefficients define the range over time. A technique for fitting a polynomial to a data set is described in [5]. The order of the fitting polynomial can be arbitrarily increased to achieve the required accuracy. For generating range delay profiles, the polynomial should be correct to within a fraction of the range gate spacing.

Once the range to the target position over the illumination time has been represented as a polynomial, the formula for the platform-jammer range over the same time period can be produced in the same fashion. Subtracting the jammer range from the target range yields the range-difference equation:

$$\Delta r(t) = (a_0 - b_0) + (a_1 - b_1)(t - t_c) + (a_2 - b_2)(t - t_c)^2 + \ldots \qquad (3.2)$$

Where the a_k terms are the coefficients of the target range polynomial, while the b_k terms come from the jammer range polynomial. The range difference Taylor series is centered on t_c, the target beam-centre time.

The range difference can be easily converted to a range delay profile by considering the time required for radar pulses to travel the round-trip distance at the speed of light:

$$T_{Delay}(t) = \frac{2}{c}\left[(a_0 - b_0) + (a_1 - b_1)(t - t_c) + (a_2 - b_2)(t - t_c)^2 + \ldots\right] \qquad (3.3)$$

It is therefore fairly simple to generate accurate range-delay profiles from platform to surface-point range data.

As an example, the goal of one jamming scenario was to introduce deceptive countermeasures into a RADARSAT S6 image. The desired target location was at approximately the same azimuth position as the jammer, and up-range by about 40% of the swath width. ECM Builder calculated the range coefficients for the target location as a_0 = 1038.7 km, a_1 = -239.0 m/s and a_2 = 23.9 m/s^2. The corresponding values for the jammer were b_0 = 1062.0 km, b_1 = -245.6 m/s and b_2 = 23.4 m/s^2. The program then calculated the final delay formula as,

$$T_{Delay}(t) = -155.472 + 0.044(t - t_c) + 0.004(t - t_c)^2\ \mu s \qquad (3.4)$$

In this case, the first and second-order delay terms would contribute less than the expected 77 ns sample-spacing over the planned transmission period of 0.5s. Therefore, it was not necessary to consider them in the calculation.

3.4 Motivation for Time-Varying Doppler Profile

The basic SAR ECM model uses Doppler shifts only to generate azimuth displacements and does not change the applied Doppler over time. According to the basic model, producing a simple down-range target requires no Doppler at all. This is based on the assumption that the jammer and the target location have the same Doppler azimuth chirp. However, this is generally not the case.

The azimuth chirp is a consequence of the SAR imaging geometry; it is a Doppler effect of the changing platform-to-surface-point range over the illumination period. The link between changing range and instantaneous frequency shift is characterized by the Doppler formula:

$$\Delta f = \frac{-2}{\lambda}\dot{r} \qquad (3.4)$$

where Δf is the Doppler shift, λ is the carrier wavelength and $\dot{r}$ is the time derivative of range. By convention, a closing velocity corresponds to a positive Doppler. The Doppler shift is proportional to the negative of the time-derivative of the range. Thus the curve representing the Doppler shift of a surface point over time is proportional to the slope of the range curve for that surface point. Where the range curve approximates a parabola, the Doppler curve approximates a straight line. The relationship is summarized below.

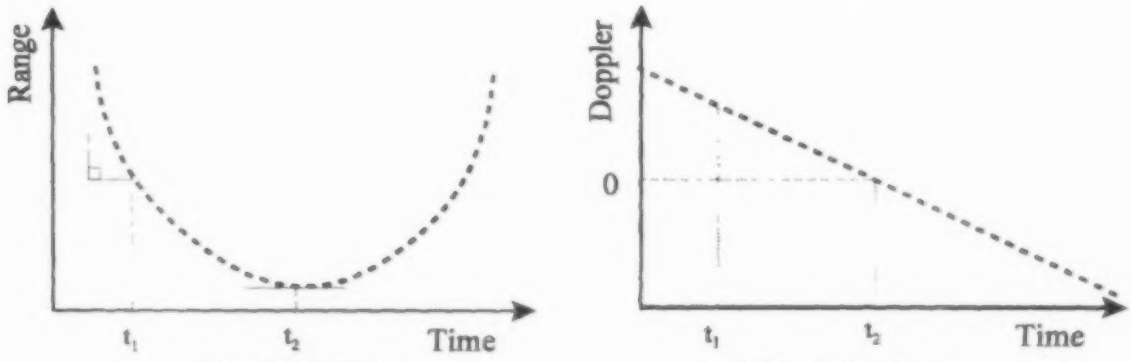


Figure 3.6: Doppler Shift is proportional to the negative slope of the range curve.

Since the shape of the range curve varies with range position, so does the Doppler curve. In general, the jammer and target location will have different range curves, and therefore different Doppler curves. The natural azimuth Doppler chirp for the two points will be different. This effect

is summarized in Figure 3.7.

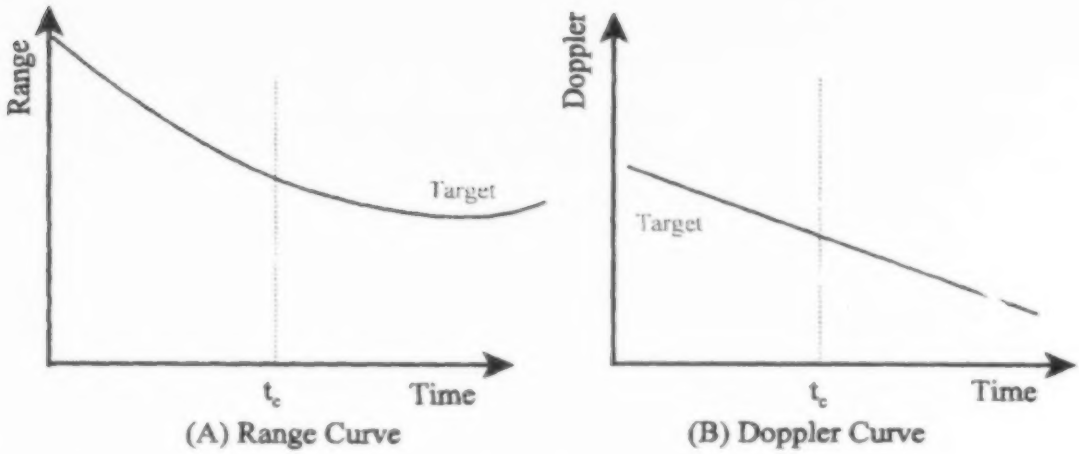


Figure 3.7: A range-curve mismatch implies a Doppler curve mismatch

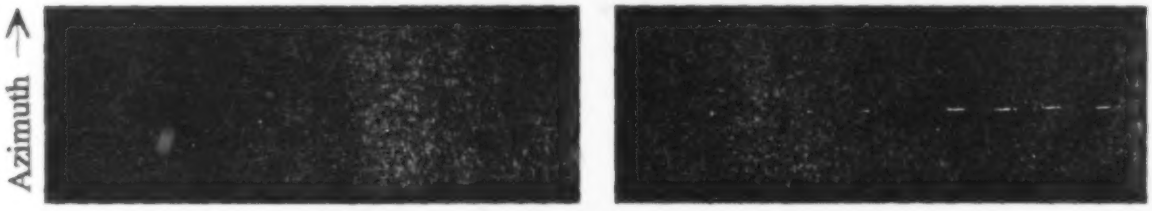
Notice that at the beam-centre time of the target (t_c), the Doppler curve of the jammer is offset from the Doppler curve of the target both in frequency (Hz) and in slope (Hz/s). In common SAR terminology, the Doppler shift at beam-centre time is referred to as the F_{DC} (*Doppler centroid frequency*), while the slope of the Doppler is called the FMR (*frequency modulation rate*). In general, the azimuth Doppler chirp of the jammer will have a different F_{DC} and FMR from the target location.

The SAR processor uses the azimuth chirp of a surface target to locate and focus it in azimuth. Therefore, the two main effects of an inaccurate azimuth chirp are incorrect positioning and focusing problems.

If the central frequency (F_{DC}) of the azimuth chirp is off by a small amount, the result will be a small, unwanted azimuth offset. If the F_{DC} error is large, significant portions of the ECM signal will be suppressed during the processing stage, resulting in loss of power and slight defocus. A very large F_{DC} error can produce an effect called an *azimuth ambiguity*, where the ECM signal becomes partially or totally aliased to a different frequency due to violation of the *Nyquist limit* for the SAR pulse repetition frequency[2]. This aliasing causes a large error in the azimuth position of the false target.

[2] The Nyquist limit defines the maximum frequency which can be represented at a particular sampling rate (in this case, the SAR PRF). Frequency content above this limit becomes aliased to a lower frequency.

If the FMR of the azimuth chirp is incorrect, the target will have focusing problems in the azimuth direction. Point targets will become spread-out and lose power. Figure 3.8 shows how a mismatch in FMR can distort linear features:



A: Targets with large FMR mismatch

B: Targets with correct FMR

Figure 3.8: FMR mismatch causes distortion of linear targets

In order to avoid such undesired effects, it is necessary to artificially modify the azimuth Doppler chirp of the jammer so that it matches the expected azimuth chirp of the target location. This is accomplished by adding a time-varying Doppler profile to the jammer's return pulses.

3.5 Determination of Doppler Profile

The Doppler compensation profile required to focus a target at a particular surface point is linked to equation 3.2, the range difference equation, in exactly the same way as the Doppler curve of a surface point is linked to its range curve. Therefore, finding the Doppler compensation profile is very simple once the range delay profile has been calculated.

Since the Doppler effect is based on a change in range, the zero order term is constant and has no effect on the Doppler. Therefore only the first and higher-order terms in the range polynomial affect the Doppler compensation parameters. However, when the range curve is used to determine the Doppler compensation profile, the curve shape (as defined by the higher-order parameters) must be much more accurate than required for finding the range delay profile. To derive reliable Doppler frequency information, the inaccuracies in curve shape should produce an error of less than a fraction (e.g. 1/4) of the carrier wavelength over the illumination time.

Given a suitably accurate range curve polynomial, the Doppler compensation can be quickly derived from the range difference equation. Taking the derivative of equation 3.2 (the range difference equation) for a particular surface point and jammer combination yields the radial velocity difference equation:

$$\Delta\dot{r}(t) = (a_1 - b_1) + 2(a_2 - b_2)(t - t_c) + 3(a_3 - b_3)(t - t_c)^2 + \cdots \qquad (3.5)$$

Substituting the Doppler formula (Equation 3.4) into Equation 3.5 produces a formula for the Doppler frequency difference between the target location and the jammer location over the illumination period of the target:

$$f_A(t) - f_B(t) = -\frac{2}{\lambda}(a_1 - b_1) - \frac{4}{\lambda}(a_2 - b_2)(t - t_c) - \frac{6}{\lambda}(a_3 - b_3)(t - t_c)^2 + \cdots \qquad (3.6)$$

Here, $\mathbf{f_A}$ is the natural Doppler frequency of the target location at time **t**, $\mathbf{f_B}$ is the Doppler frequency of the jammer location at time **t**, and $\boldsymbol{\lambda}$ is the SAR carrier wavelength. This equation can be broken into several parts:

The Doppler shift difference at the target's beam centre time is denoted Δf_{DC} :

$$\Delta f_{DC} = -\frac{2}{\lambda}(a_1 - b_1) \qquad (3.7)$$

The linear time-dependent parts of equation 3.6 can be denoted as ΔFMR:

$$\Delta FMR = -\frac{4}{\lambda}(a_2 - b_2) \qquad (3.8)$$

Assuming a quadratic polynomial describes the range curve to within a quarter of a wavelength, the required Doppler compensation profile can then be represented as

$$F_{Comp}(t) = \Delta f_{DC} + \Delta FMR(t - t_c) \qquad (3.9)$$

Similar equations with additional terms may be used if required to achieve sufficient precision.

3.6 Motivation for Transmission Scheduling

A significant limitation of the basic model is that the jammer is contrained to transmitting only when illuminated by the SAR mainbeam. This limitation severely restricts azimuth placement because the amount of azimuth offset achievable through a Doppler shift alone is limited.

In order to achieve high azimuth resolution, a SAR system gathers hundreds of returns from a surface point over an *integration interval* which corresponds to the central part of the mainbeam illumination time. Only returns received during this integration interval can be focused onto the surface point. Therefore, to put a target at a particular location, a jammer has to transmit when the SAR processor 'expects' to receive returns from that location. ECM signals transmitted outside the integration period of a surface point will never focus at that location.

As a consequence of this characteristic of SAR, a jammer which transmits only when illuminated by the main-beam can only produce false targets with a small azimuth offset. The integration interval of a target location with a large azimuth offset will not overlap the illumination period of the jammer. For moderate azimuth offsets, the illumination period will only partially overlap, reducing processing gain. This azimuth offset limitation is illustrated in Figure 3.9, below.

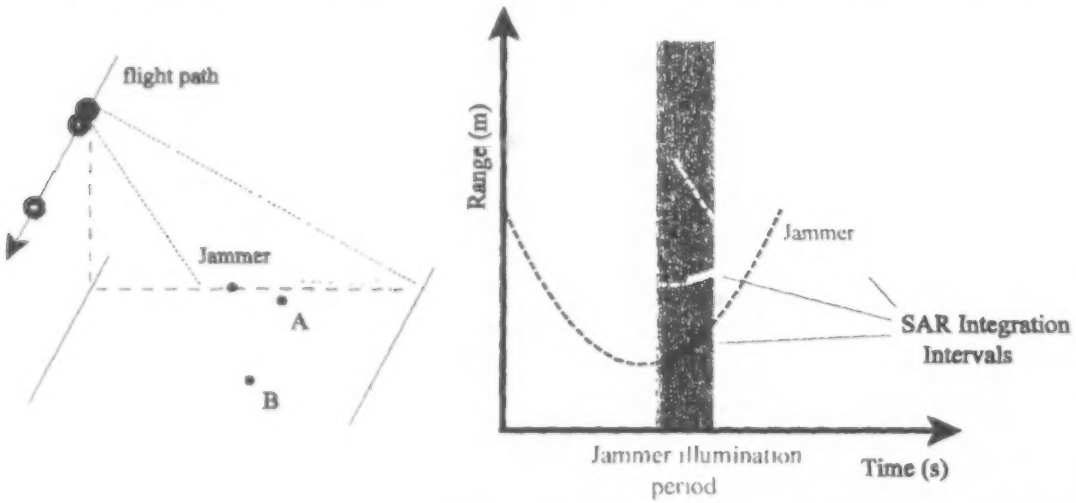


Figure 3.9: Target integration interval might not overlap jammer illumination period.

For the situation depicted in Figure 3.9, some energy from the jammer transmission period can be applied to target A. However, target B cannot be drawn under the basic model constraints because the jammer does not transmit during target B's integration period.

The mainbeam transmission time problem is a very restrictive factor in the basic model limiting the placement options for well-formed deceptive countermeasures against spaceborne SAR. For instance, assuming a jammer illumination period of 1.0s and an integration period of 0.45s, Figure 3.10 shows the width of the strip which can be covered for a typical RADARSAT pass.

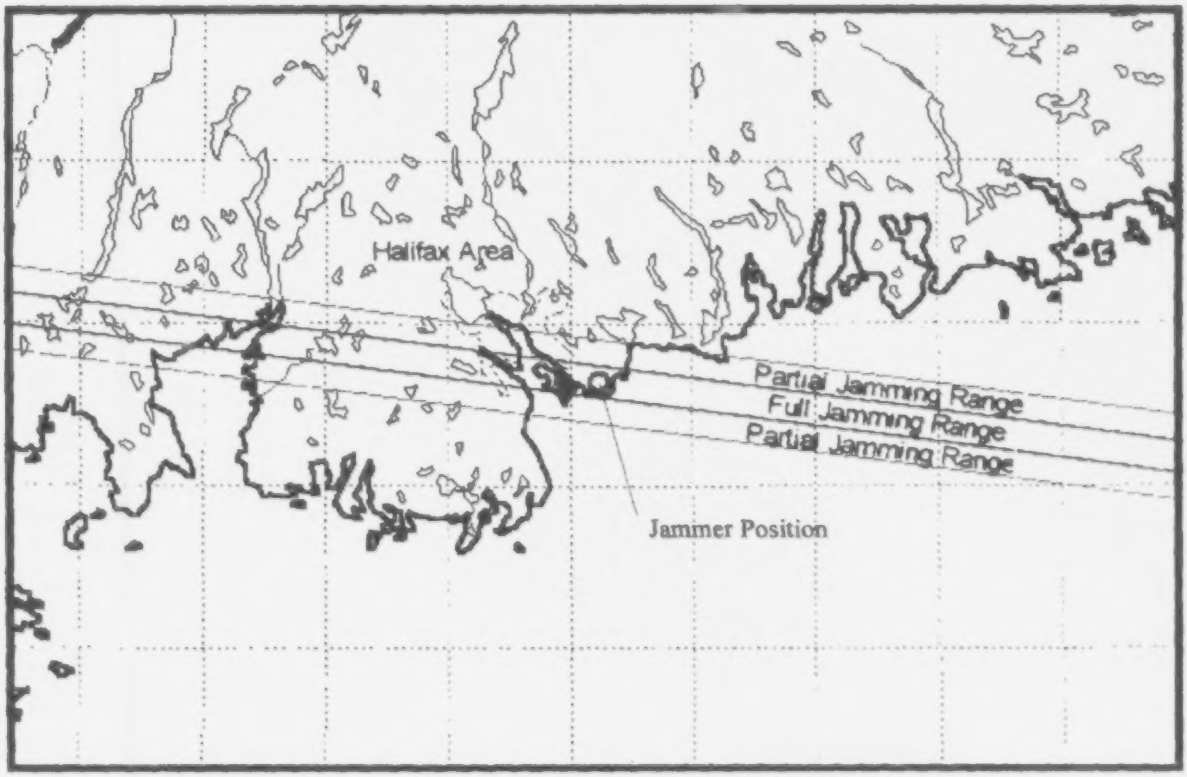


Figure 3.10: Countermeasure placement options for a typical RADARSAT pass: basic model

The jammer location is marked by the circle in the centre of the map. Targets placed within the strip marked 'full jamming range' can be drawn over their entire integration period. Their entire integration period lies within the illumination period centered at the jammer. For the scenario described above, this fully jammable region is only 3.6 km wide[3]. Only a portion of the integration time can be jammed for targets in the 'partial jamming range' strips, as only part of their integration period lies within the 1.0s jammer illumination period. Targets drawn in these regions will have lower power and less azimuth focus. Locations outside the area marked on Figure 3.10 can't be covered by ECM signals transmitted during the jammer illumination period.

[3] RADARSAT's ground velocity x (jammer illumination period - target integration period) = 6.6 km/s x (1.0 s - 0.45 s) = 3.63 km

This azimuth placement limitation cannot be circumvented simply by applying large Doppler shifts because the azimuth bandwidth used in the SAR processor cannot be more than the pulse repetition frequency (PRF). If a large Doppler shift is used, part or all of the return signal will be aliased, undergoing a shift of one PRF in effective frequency. This aliasing causes a discrete jump in focused azimuth position. This effect is responsible for the so-called 'Doppler ambiguities' which appear when large Doppler offsets are used for image placement. In fact, applying Doppler to generate even a modest azimuth shift will cause the ECM signal to correlate with less of the processed chirp bandwidth, resulting in a lower focused brightness. Both of these effects are evident in Figure 3.11, below.

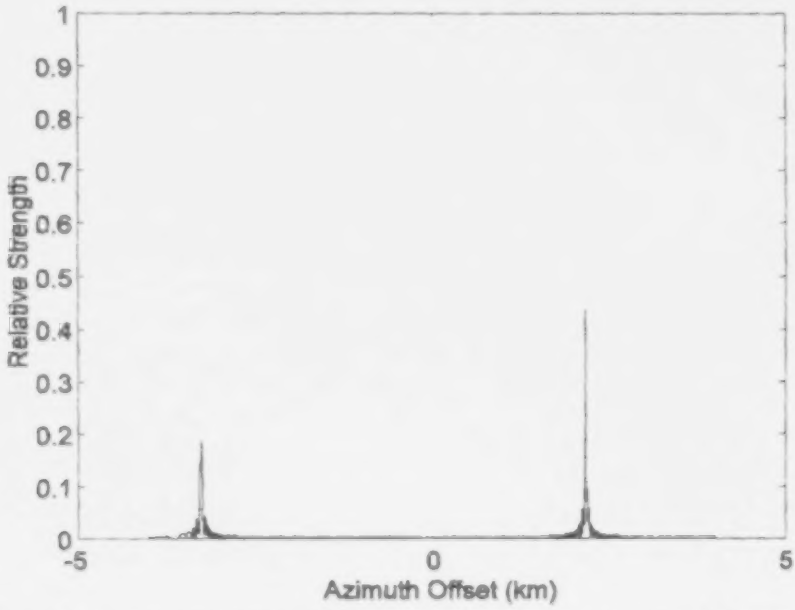


Figure 3.11: Azimuth ambiguity created by Doppler shift of 0.4 PRF

Figure 3.11 was created by generating a typical RADARSAT Doppler chirp (without the antenna pattern) and correlating it with a similar Doppler chirp shifted upwards in frequency by 40% of the PRF of 1350 Hz. The plot was generates assuming an FM rate of 1900 Hz/s and a platform ground velocity of 6.7 km/s. The Doppler shift generates an azimuth offset in the main spike on the right, but also introduces a secondary spike, a *Doppler ambiguity*, due to aliasing of the higher frequency portion of the chirp. The signal is now split between the two spikes, each less than half the strength of an unshifted chirp.

Since the Doppler-shifting technique can only generate small azimuth offsets, the jammer must transmit outside its main-beam illumination period to place targets at large distances in azimuth. The transmission schedule of the jammer must be based on when the target location, and not the jammer, is illuminated by the SAR's mainbeam.

If a jammer has the capability to coordinate transmissions to coincide with the target illumination period, the maximum azimuth placement range would be greatly extended. Under these circumstances, azimuth range is likely to be limited by the ability of the jammer to transmit with sufficient power to overcome the loss of SAR receive antenna gain. An additional challenge could be the ability to receive the incoming signal outside the main antenna beam.

3.7 Determination of Transmission Schedule

In the basic SAR ECM model, the transmission schedule of the jammer coincides with the jammer's illumination period. The system could be made to transmit during this period by setting a threshold on received power above which transmission takes place. In order to place false targets at large azimuth offsets, however, the jammer needs to transmit outside its own illumination period. The jammer must transmit ECM while the target location is illuminated by the SAR mainbeam[4]. One can determine when the SAR illuminates the target location by modeling the SAR imaging geometry in software, similar to how the time-varying delay and Doppler profiles are determined.

In fact, the ability to calculate the illumination time is required even to find the correct delay and Doppler parameters, since these calculations depend on sampling the surface-point to platform range *during the illumination period*. This section of the report outlines how a software tool such as ECM Builder can determine the illumination periods of arbitrary surface points, and describes some of the associated implementation issues when attempting to design a jammer which can execute the scheduling.

The illumination period of a surface point is the interval over which the point is illuminated by the SAR mainbeam. The instant in the middle of the illumination period, when the point is at the azimuth center of the antenna mainlobe, can be called the *Beam Centre Time* (BCT). A program can determine the BCT by finding when the satellite antenna is pointing directly towards the surface point in question. This is done by modeling the orientation of the SAR platform in 3-dimensional space as it travels along its flightpath and making appropriate assumptions on the antenna pointing angle relative to the platform.

ECM Builder defines the orientation of the SAR platform in the same way for airborne and space-based SAR. The orientation consists of a rectangular coordinate system where the forward axis points in the direction of flight, the vertical axis points away from the platform nadir and the side axis completes a right-handed coordinate system. Sometimes assumptions have to be made on the SAR antenna orientation relative to the platform. The RADARSAT SAR antenna, for instance, is assumed to point directly to the side, with zero squint angle (for this calculation, only the azimuth orientation, and not the elevation angle of the antenna is important). Though this is RADARSAT's nominal orientation, in practice there is usually a small, uncontrolled squint angle. Small pointing errors such as this can cause some inaccuracy in the BCT calculations, but typically not enough to degrade the results.

4 As stated in Section 3.6, only jamming signals transmitted during the target point's integration interval, a subset of the integration interval, will focus at the target location. However, it does no harm to transmit during the entire illumination interval, since this is how a real target would behave.

By modeling the platform trajectory, a program can find the point in time when the azimuth angle from the platform to the surface point matches the antenna pointing angle. If the surface point is in the SAR image swath, this is the Beam Centre Time (BCT) of the surface point, i.e. the center of the illumination period. Due to a number of factors, including the uncertainty in antenna pointing angle, it is difficult for a program such as ECMB to produce absolute BCT predictions accurate enough for transmission scheduling. However, the predicted BCT *difference* between two surface points can be much more accurate than an absolute value, especially if the squint angle is poorly known.

These BCT offset predictions could be used to schedule jammer transmissions relative to the BCT of a reference location. For instance, the jammer might passively observe its own BCT and use this as a reference to place false targets further along the SAR platform's ground track. There are several other possible operational scenarios. More research is needed to determine the best way to implement jammer transmission scheduling.

5.0 Conclusions

The *basic SAR ECM model* is effective for creating false targets with small offsets in range and azimuth. However, the basic model cannot produce high-quality targets at large range and azimuth offsets. The assumption of constant Doppler and repeat delay, together with the constraint of jammer transmission only while illuminated, limit the effective range of the basic model.

In order to focus targets at large range offsets it is necessary to use both a time-varying repeat delay and a time-varying Doppler profile. The timing error from using a constant repeat delay can result in range 'wander', azimuth blurring and loss of power. The error introduced by using a constant Doppler can cause blurring, distortion and undesired shifts in azimuth.

Placing a false target at a large azimuth offset (e.g. outside the azimuth mainbeam) requires control over the jammer transmission period in addition to time-varying Doppler and repeat delay. The jammer must transmit during the target illumination period instead of the jammer illumination period.

The *expanded SAR ECM model* generally uses linear slides in delay and Doppler to focus targets at large range offsets. Higher-order, non-linear delay and Doppler profiles may sometimes be necessary to properly compensate for a distant target location if the geometry is unusual (e.g. extreme offsets in azimuth). The ECM Builder program extracts the delay and Doppler profiles from the platform-to-surface-point range curve. It uses polynomial fitting and simple arithmetic operations to calculate the necessary Doppler and delay parameters.

The ECM Builder software finds the correct jammer transmission schedule by determining when the SAR is pointing at the target location. A time difference between the beam centre time for the jammer and surface point is calculated accurately though the absolute time may be off by several seconds. This is based on calculations of SAR platform orientation and trajectory as well as some assumptions on antenna pointing angle.

The expanded model relies on SAR platform trajectory predictions to calculate compensation parameters. If the trajectory prediction is of low quality, the maximum displacement in range and azimuth at which a deceptive false target can be reliably generated will be reduced.

Many current jammers are capable of implementing the range and Doppler profiles needed to focus targets at large range offsets. However, the ability to shift the jammer transmission period is not as easily implemented and will probably require additional software support.

6.0 Recommendations

Deceptive SAR ECM techniques should use time-varying repeat delays and time-varying Doppler profiles for targets with large range offsets or azimuth offsets. Since software such as ECM Builder can perform the necessary calculations automatically, time varying profiles should be used whenever the flightpath of the SAR platform is known or can be estimated.

Alternative methods of controlling jammer transmission scheduling should be investigated. Better control of the jammer transmission period will allow placement of false targets at much larger azimuth offsets than the Doppler-shifting technique.

More research should be conducted on the effects of SAR platform trajectory prediction inaccuracies on the derived compensation parameters. If possible, a method should be developed to quantify the relationship between the maximum error in the trajectory estimate and the maximum reliable target displacement in range and azimuth for geometries of interest.

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SECURITY CLASSIFICATION OF FORM
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(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.)

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2. SECURITY CLASSIFICATION (overall security classification of the document, including special warning terms if applicable)

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3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C or U) in parentheses after the title.)

An Expanded Model for SAR Countermeasures (U)

4. AUTHORS (Last name, first name, middle initial)

Jamieson, Michael

Saper, Ron

5. DATE OF PUBLICATION (month and year of publication of document)	6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)	6b. NO. OF REFS (total cited in document)
December 1999	32	5

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Contractor Report

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

Defence Research Establishment Ottawa
National Defence
Ottawa, Ontario K1A 0Z4

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)	9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)
1AF12	W7714-7-0114

10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)	10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor)
DRDO CONTRACTOR REPORT CR 2000-021	

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SAR
synthetic aperture radar

#514091